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Low carbon and low embodied energy materials in buildings: A review

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ABSTRACT

This paper presents a review of the literature on low carbon and low embodied energy materials in buildings. Embodied energy is defined and discussed vs. operating energy of buildings and its growing importance due to the implementation of the Energy Building Performance Directive (EBPD) in Europe as example. The difficulty of measuring embodied energy and the difficulty in comparing published data are highlighted, showing an example of proposed new methodology found in the literature. Relationship between embodied energy and embodied CO_2 or CO_2 footprint is defined. Different materials defined in the literature as low carbon materials are referred, such as cement and concrete, wood, bricks, rammed earth and sandstone. The review shows the research efforts found in the literature to develop new materials with less embodied energy. Finally, the effect of material substitution in the embodied energy of a building is reviewed in the literature.

Contents

1. Introduction

The notion of "embodied energy" was first used in the late 1970s for different purposes, In energy analysis [1,2] energy inputs to a system are aggregated from all subsidiary pathways to yield the total embodied energy or gross energy requirement. It therefore embraces the whole life cycle concept subsequently utilized in LCA studies. Van Gool [3] evaluated the minimum product ("process" plus "embodied") energy required for different types of chemical process equipment, often termed "unit operations". Fig. 1 shows a typical trade-off between process and embodied energy [4], where a minimum total energy requirement can be observed that is somewhat greater than the thermodynamic minimum (based on the so-called Gibbs free energy [3]). The notion of embodied energy has subsequently been seen as a fundamental or intrinsic part of the total energy needed to

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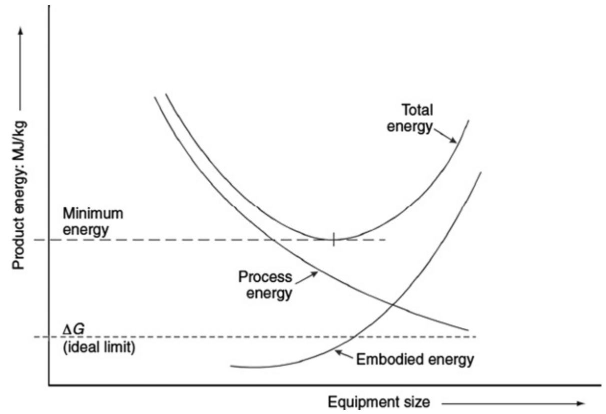

Fig. 1. Product (process + embodied) energy requirements associated with process equipment [3,4].

construct and operate process or other equipment. Similarly, embodied energy (and carbon) is now equally viewed as being important in the context of buildings [2,5–9] and construction materials [10]. Odum [11] and Hammond [12] regarded the concept of embodied energy obtained from energy analysis as only a variant of a broader property that he developed. Unusually, he took account of solar energy input into the economy, previously ignored by energy analysts.

Embodied energy has been defined by several authors, who give different nuances to the concept. Koskela [13] calls "embodied energy" to the energy consumed in production of the material. Gonzalez and Navarro [14] assert that building materials possessing high-embodied energy could possibly result in more carbon dioxide emissions than would materials with low embodied energy. According to Miller [15], the term "embodied energy" is subject to various interpretations rendered by different authors and its published measurements are found to be quite unclear. Crowther [16] defines embedded energy as "the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings." Treloar et al. [17] state, "Embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials)." Another characterization given by Bousted and Hancock (as cited by Langston and Langston [18]) is, "Embodied energy is defined as the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like…" Likewise, a more comprehensive definition, provided by Ding [20], explains that "embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building."

On the other hand, the total life cycle energy of a building includes both embodied energy and operating energy [16,20–24], being defined as:

(1) *Embodied energy* (*EE*): sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal; and
(2) *Operating energy* (*OE*): expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

Until recently, in life cycle analyses only operating energy was considered, due to its larger share in the total life cycle energy. However, the increase of energy efficient equipment and appliances, along with more advanced and effective insulation materials, the potential for curbing operating energy has increased and as a result, the current emphasis has shifted to include embodied energy in building materials [16,20,25–28]. Crawford and Treloar [29] suggest that, in Australia, the embodied energy contained in a building is 20–50 times the annual operational energy needed for the building.

Pacheco-Torgal et al. [30] quantified the influence of operational energy vs. embodied energy with the new Energy Performance Building Directive (2002/91/EC-EPBD) in 97 apartment-type buildings in Portugal. The operational energy in today's buildings was an average of 187.2 MJ/m^2/yr and the embodied energy accounted for approximately 2372 MJ/m^2, representing about 25.3% of the former for a service life of 50 years. The major decrease of operational energy due to the implementation of the EPBD means that the energy required for the manufacturing of building materials, the embodied energy, could represent in a near future almost 400% of the operational energy. Moreover, the authors state that replacing up to 75% of the Portland cement with mineral admixtures could allow energy savings needed to operate a very high efficiency building during 50 years.

Langston and Langston [18] suggest that, while measuring operating energy is easy and less complicated, determining embodied energy is more complex and time consuming. Moreover, there is no generally accepted method available to compute embodied energy accurately and consistently [15,16], therefore, wide variations in measurement figures are inevitable [15,16,18,20,31].

Dixit et al. [24] presented a review on the embodied energy determination methods. Within these methods, statistical analysis, process-based analysis, economic input/output-based analysis, and hybrid analysis are identified. These methods differ in their collection of data about energy inputs in the material production and support processes, and each possesses advantages and disadvantages discussed in the paper. Moreover, the authors identify that incompleteness and inaccuracy are two key issues associated

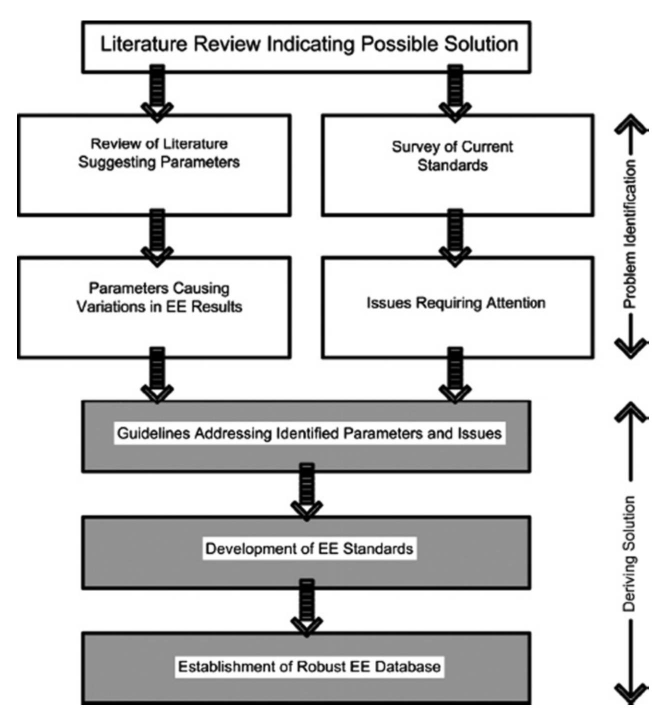

Fig. 2. Proposed approach to establish embodied energy protocol according to Dixit et al. [24].

with these methods, which may cause variation in embodied energy values. Moreover, the authors recommend a protocol for embodied energy calculations, shown in Fig. 2.

Recent studies have considered the significance of embodied energy inherent in building materials, with a specific focus on this fraction of sequestered energy [21]. Reddy [32] stated that as we moved away from zero energy materials to more modern building materials, it became imminent to spend more energy and natural resources (going from soil, leaves or timber to metals, inorganic binders and plastics); these modern materials are energy intensive and are hauled over long distances before being used for construction.

A modest knowledge and awareness of the embodied energy contents of building materials could encourage the use of not only production and development of low embodied energy materials, but also their preference among construction design and industry to curb energy use and carbon dioxide discharge [20].

A study carried out by Thormark [33] showed that embodied energy was 40% of total energy needed for a lifetime expectancy of 50 years but through material substitution, the embodied energy could be decreased by approximately 17%. Embodied energy of construction materials depends on the manufacturing process, the availability of raw material in vicinity, the efficiency of production, and the quantity of material used in actual construction. According to Dixit et al. [21] embodied energy data depends on ten parameters, which are system boundaries, methods of embodied energy analysis, geographic location of study area, primary and delivered energy, age of data sources, source of data, completeness of data, technology of manufacturing processes, feedstock energy consideration, and temporal representativeness. Embodied energy of different construction materials is dependent on its production process [34].

There is a clear relationship between embodied energies and CO_2 footprint for primary production, which both are usually assessed by input/output analysis. Ashby [35] states that the embodied energy is the energy, excluding that from bio-fuels, that is used in making 1 kg of material from its ores and feedstock in a material production plant; while the CO_2 footprint is the sum of all the contributions per unit mass of usable materials exiting the plant. In transport and in most (but not all) industrial processes there is a correlation between CO_2 emission in kg and the energy consumption in MJ:

$$CO_2 \text{ footprint} \cong 0.08 \times \text{Energy consumption.}$$

For example, in CES Selector, one of the available databases in the market, data are calculated using values for a developed country with an energy mix of 75% fossil fuel, and a conversion efficiency of 38%, giving an oil equivalence of 7 MJ and a carbon footprint of 0.5 kg CO_2/kWh (oil equivalent OE, kg of crude oil with the same energy content as 1 kg of the fuel). Because of the low precision of eco-attributes related to energy and carbon footprint, it is necessary to consider elevated uncertainty (20%) for decision making.

A step forward was presented by Jiao et al. [36] presenting the correlation between the embodied energy and the cost of individual building components, which was stronger for buildings in the same country and was related to the national energy consumption per GDP (energy intensity).

2. Low carbon materials

The use of modern building materials should be carried out paying attention to [32] the energy intensity of materials; the natural resources and raw materials consumed; the recycling and safe disposal; and the impact on the environment.

Much effort has been devoted recently to document the environmental impacts of the different materials used in construction and most of the results are incorporated in commercial software, handbooks [37,38], websites (e.g. www.greenbooklive.com) and tools (e.g. BREEAM) which are widely used by academia and industry. The "Environmental Profiles" database for materials, produced by BRE, is an attempt to produce standardized environmental data on construction materials in the UK [38]. Embodied energy coefficients of materials were initially produced for New Zealand [39,40]. The Inventory of Carbon and Energy [41,42] summarizes embodied energy and CO_2 coefficients for building materials, using data collected from primary and secondary sources in the public domain, and employs a cradle-to-gate analysis for the majority of the materials included.

2.1. Raw materials CO_2 vs. fuel-derived CO_2

CO_2 emissions from any manufacturing process have to be divided into two categories: those simply derived from carbon compounds in the raw materials that are converted to CO_2 during the manufacturing process, which are known as "raw materials CO_2", and those produced by the combustion of fossil fuel necessary to drive the manufacturing process, which are usually called "fuel-derived CO_2". The former is much easier to predict than the latter, because one usually knows very precisely the composition of the raw materials and the products [43].

The carbon emissions of building materials are made up of the direct carbon emission and the indirect carbon emission [44]. The carbon emissions of the raw materials and building materials' producing process are the two important parts to evaluate the direct carbon emission. Indirect carbon emission which was generated from the depreciation of equipment and buildings, the management in each link and the environmental process of garbage processing and transportation should be estimated.

2.2. Cement and concrete

The impact of concrete buildings on environment is mainly due to clinker, which is the main material used all over the world to produce cement and which releases a bit less than 1 t of CO_2 per ton of clinker produced [32,45]. Reducing the amount of clinker by substituting with complementary cementing materials (CCM) results in lesser CO_2 emissions.

Habert and Roussel evaluate two different environmental options for sustainable concrete mix-design [45]. The first one is the substitution of clinker by mineral additions in cement in order to reduce the environmental cost of the material for a given volume of concrete produced. The second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. It has been estimated that, in France, the CO_2 emissions could be reduced by 15% by increasing the level of substitution in concrete. It has also been estimated that the second option could lead to reduction of the order by 30%.

Gartner [43] discusses the practicality of replacing Portland cements with alternative hydraulic cements that could result in lower total CO_2 emissions per unit volume of concrete of equivalent performance. Currently, the cement industry is responding rapidly to the perceived societal need for reduced CO_2 emissions by increasing the production of blended Portland cements using supplementary cementitious materials that are principally derived from industrial by-products, such as blast-furnace slags and coal combustion fly ashes. However, the supplies of such by-products of suitable quality are limited. An alternative solution is to use natural pozzolans, although they must still be activated either by Portland cement or lime or by alkali silicates or hydroxides, the production of all of which still involves significant CO_2 emissions.

Moreover, concretes based on activated pozzolans often require curing at elevated temperatures, which significantly limits their field of application.

The most promising alternative cementing systems for general concrete applications at ambient temperatures currently appear to be those based at least in part on calcium sulfates, the availability of which is increasing due to the widespread implementation of sulfur dioxide emission controls [43]. These include calcium sulfoaluminate–belite–ferrite cements of the type developed in China under the generic name “Third Cement Series” (TCS) and other similar systems that make good use of the potential synergies among calcium sulfate, calcium silicate and calcium aluminate hydrates.

Reddy and Kumar [46] studied embodied energy of cement stabilised rammed earth (CSRE) walls. Influence of soil grading, density and cement content on compaction energy input was monitored. It was noted that compaction energy increases with increase in clay fraction of the soil mix and it is sensitive to density of the CSRE wall. Compaction energy varies between 0.033 MJ/m^3 and 0.36 MJ/m^3 for the range of densities and cement contents attempted, and energy expenditure in the compaction process is negligible when compared to energy content of the cement. Thus CSRE walls prove to be energy efficient and low carbon option.

Emmanuel [47] defined Environmental Sustainability Index for wall materials according to their environmental suitability. It was concluded that even if wattle and daub walls have good environmental performance, cement masonry unit (CMU) wall could be built faster due to the bigger size of masonry units and better dimensional tolerance. But with technological improvement non-conventional options prove to be better at environmental performance.

According to Dias and Pooliyadda [48] all building elements (e.g. brick wall), materials (e.g. bricks), and primitive raw materials (e.g. clay) can be placed in an aggregation–decomposition hierarchy. Each stage of a building material can be considered to have energy inputs that are defined as proximate (i.e. production energy and transport of raw materials) and remote (i.e. embedded energy of raw materials).

According to energy quality calculations carried out (based on efficiency considerations), 1 GJ of electricity is equivalent to 5 GJ of biomass energy on the one hand, and to 2.78 GJ of fossil fuel energy on the other. For the conversion system to be mutually consistent, the biomass to fossil fuel factor is obtained as 1.8. The energy contents of building materials could thus be compared on the basis of an equivalent amount of the lowest quality. Energy (i.e. biomass energy), and the energy contents were obtained on a bioequivalent basis.

The analysis carried out indicates that amongst the more common construction materials considered, the lowest energy option is timber, while the highest is steel, with concrete in between. Timber products have negative carbon coefficients as well, i.e. they store more carbon than is emitted in their use for construction while the carbon emissions from steel products will be greater than those from concrete products.

Gartner [43] suggested replacement of Portland cements with alternative hydraulic cements containing blast-furnace slag and coal combustion fly ashes that could result in lower total CO_2 emissions per unit volume of concrete of equivalent performance. Habert and Roussel [45] studied two different environmental options for sustainable concrete mix-design. The first one is the substitution of clinker by mineral additions in cement in order to reduce the environmental cost of the material for a given volume of concrete produced. The second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. It has been estimated that the CO_2 emissions could be reduced by 15% on increasing the level of substitution in concrete. It has also been estimated that the second option could lead to reduction of the order of 30%.

Talukdar et al. [49] studied the potential use of waste materials such as crushed glass, ground tire rubber, and recycled aggregate in concrete with compressive strength and elastic modulus as the primary parameters of interest. They demonstrated that ground tire rubber introduced significant amounts of air into the mix and adversely affected the strength. Adding a defoamer was able to remove part of the excess air from the mix, but the proportional strength improvements were found implying that air left in the defoamed mixture had undesirable characteristics. Later, freeze–thaw tests were performed to understand the nature of air in the defoamed mixtures, and results demonstrated that this air is not helpful in resisting freeze–thaw resistance either.

One step forward is the use of nano- and micro-particles in cementitious materials, but as stated by Jayapalan et al. [50] these particles can decrease the sustainability of the cement materials. His research shows that the use of natural or by-product nanoparticles or a filler with lower embodied energy and lower emissions (such as limestone) is an adequate path to sustainability.

2.3. Wood

Buchanan and Levine [51] showed that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminum, steel and concrete. Changing toward the use of wood in buildings is possible because the low fossil fuel requirement for manufacturing wood compared with other materials is much more significant in the long term than the carbon stored in the wood building products.

The results presented show that a 17% increase in wood usage in the New Zealand building industry could result in a 20% reduction in carbon emissions from the manufacture of all building materials, being a reduction of about 1.5% of New Zealand's total emissions. The reduction in emissions is mainly a result of using wood in place of brick and aluminum, and to a lesser extent steel and concrete, all of which require much more process energy than wood. There would be a corresponding decrease of about 1.5% in total national fossil fuel consumption.

Nassen et al. [52] compared buildings with concrete frames and wooden frames taking into account their life-time carbon dioxide emissions as well as their total material, energy and carbon dioxide costs. By using energy systems scenarios they investigated the impact of higher energy and carbon dioxide prices as well as of the availability of carbon capture and storage (CCS) technologies. According to these authors, wooden frames cause lower carbon dioxide emissions given today's energy system, but concrete frames obtain about the same emissions as the wood frame in a system where CCS is not used for wood incineration in the demolishing phase.

2.4. Bricks

Jiao et al. [53] used solid wastes to launch the experimental work on low carbon building materials. They studied the impact of solid wastes on the mechanical properties of the new low carbon building brick. Four types of solid wastes were considered: dredged mud, fly ash, steel slag, and calcium carbide sludge. Results showed that the content of marine engineering waste dredged mud has a significant influence on the performance of the low carbon brick. According to the test methods, the content of dredged soil can reach a maximum of 65%. Fly ash, calcium carbide mud, and slag, had a great influence on the mechanical properties of autoclaved dredged mud brick and an optimum ratio could be

found. Under the experimental conditions, the best ratio of fly ash was 15%, calcium carbide and steel slag are 12% and 10%, respectively.

Jiao et al. [53] studied the carbon emissions of autoclaved fly ash bricks. The carbon emissions and the percentage of each part to the total carbon emissions were estimated. The results show that the carbon dioxide emissions of 1 m^3 fly ash bricks was estimated to be 435.92 kg, the carbon emissions of raw materials accounted for 81.6% of the total emissions, the carbon emissions of raw material preparation accounted for 65.8%, the carbon emissions of material transportation accounted for 0.1%, and the carbon emissions of raw material preparation accounted for 18.4% of the total carbon emissions.

According to Reddy [32] stabilized mud blocks (SMB) are energy efficient eco-friendly alternatives to burnt clay bricks. These are solid blocks manufactured by compacting a mixture of soil, sand, stabilizer (cement or lime), and water. These blocks save around 60–70% of the energy used in burned bricks and can use of the industrial wastes like stone quarry dust, fly-ash, etc. in their composition.

Similarly, Kinuthia and Oti [54] used lime and Portland cement as an activator to an industrial by-product (ground granulated blastfurnace slag—GGBS) to stabilize kaolinite clay and lower oxford clay for non-fired clay building material development. GGBS has extremely low energy usage and CO_2 emission when compared to Portland cement. The energy use of 1 t of GGBS is 1300 MJ, with a corresponding CO_2 emission of 0.07 t, while the equivalent energy use of 1 t of Portland cement is about 5000 MJ, with at least 1 t of CO_2 emitted to the atmosphere. Moreover, GGBS is a material with availability locally, in line with the sustainable parameters.

2.5. Rammed earth

Large numbers of rammed earth buildings have been constructed in the recent past across the globe [32]. There are two types of rammed earth constructions, stabilized and non-stabilized rammed earth. Non-stabilized rammed earth is made from soil, sand, and gravel, whereas stabilized rammed earth contains additives (cement or lime, sand and gravel). Non-stabilized rammed earth walls are nearly zero carbon options, but their drawbacks lead to the addition of additives in real buildings. Reddy and Kumar [46] monitored the influence of soil grading, density and cement content on the compaction energy input. Major conclusions of the investigations were that the compaction energy increases with increase in clay fraction of the soil mix and it is sensitive to density of the wall, the compaction energy varies between 0.033 MJ/m^3 and 0.36 MJ/m^3 for the range of densities and cement contents attempted, the energy expenditure in the compaction process is negligible when compared to energy content of the cement; and the total embodied energy in these walls increases linearly with the increase in cement content and was in the range of 0.4–0.5 GJ/m^3 for cement content in the range of 6–8%.

Serrano et al. [55] studied the mechanical and thermal properties of stabilized rammed earth doped with phase change materials (PCM). The stabilizers studied were lime, straw, alabaster, and pneumatic fibers. The authors present optimum formulations from DoE model equations, which are thermally analyzed to evaluate the effect of the addition of PCM. Finally, the LCA carried out shows that incorporating microencapsulated PCM in the stabilized rammed earth increases up to 4.5 time the impact point of the material, recommending the use of macroencapsulated PCM in rammed earth buildings.

2.6. Sandstone

Crishna et al. [56] carried out a process based on LCA of the dimension stone production in the UK. From a survey of eight production operations, the calculated carbon footprint of sandstone was 77 kg CO_{2e}/tonne, of granite 107 kg CO_{2e}/tonne, and of slate 251 kg CO_{2e}/tonne. These values would be considerably higher for stone imported from abroad due to the impact of transport. Authors stated that reducing the use of imported stone would contribute to emissions reduction targets.

According to Reddy [32,57] a mixture of lime, fly ash and stone crusher dust can be compacted in a high-density block. Lime reacts with fly ash minerals forming water insoluble blonds imparting strength to the block.

3. Effect of the material substitution in the embodied energy of a building

Several studies on the effects of material substitution in the embodied energy of a building have been made. Scheuer et al. [58] conclude that high-embodied energy components are often subjected to a wide range of replacements. A comparison of beams at the new airport outside Oslo showed that the total energy consumption in the manufacturing of steel beams is two to three times higher, and the use of fossil fuels 6–12 times higher, than in the manufacturing of glulam beams [59]. Buchanan suggests that increasing the emphasis on wood as a building material could have significant implications for global energy requirements and global carbon dioxide emissions [51]. Studies of Dutch residential construction revealed that an increase in wood use could reduce CO_2 emissions by almost 50%, compared with traditional Dutch construction [60]. These studies either focus on a specific material or component, or they assume radical technical and essential innovations. Darwale and Ralegaonkar [23] state that the construction process should be made more environmental friendly by replacing part of energy intensive building materials by water or recycled materials. For example, the use of prefabricated building elements replacing energy intensive clinker in Portland cements (fly ash, furnace slag, etc.), minimizing the production energy in cement, using timber-based material and recycling steel can save up to 32% of CO_2 emissions and up to 80% energy in the production process.

Besides minimizing embodied energy, it is equally important to produce buildings with a high recycling potential in order to reduce the use of energy and resources over an extended length of time. Recycling potential of buildings is a relatively new concept and has only been assessed in a few studies thus far.

In a Japanese study by Gao et al. [61], potential energy saving in material production was studied in three building designs. In each design, a maximum use of recycled materials and products were assumed. The result indicated that energy use for material production decreased by about 25%, compared to a case where recycled materials were not used. In a Swedish study, a single-family house was built in 1997 with a large proportion of recycled materials and components. The construction of this house was compared to the case if all materials would have been new. The energy saved, achieved through the use of re-used materials, was about 40% [62].

In a German study, a different approach was used to assess the potential energy saving by recycling [63]. The recycling potential was defined as the environmental impact reduction due to a total abolition of disposal processes. The assumption was a theoretical recycling rate of 100%. Results indicated a recycling corresponding to about 12% of the building's total energy use for material production.

A similar approach was used and described in a Swedish study, where the recycling potential was estimated for low-energy dwellings [64]. In this particular study, the assumed recycling rates and forms did not represent the general practice but were occasionally used by those only with previous experience. Results

Table 1
Embodied energy in various wall, floor and roofing systems [32].

Type of building element	Energy per unit (GJ)
Burnt clay brick masonry (m^3)	2.00–3.40
SMB masonry (m^3)	0.50–0.60
Fly ash block masonry (m^3)	1.00–1.35
Stabilized rammed earth wall (m^3)	0.45–0.60
Non-stabilized rammed earth wall (m^3)	0.00–0.18
Reinforced concrete slab (m^2)	0.80–0.85
Composite SMB masonry jack-arch (m^2)	0.45–0.55
SMB filler slab (m^2)	0.60–0.70
Non-reinforced masonry vault roof (m^2)	0.45–0.60

indicated that the potential energy saving was approximately 35% of the building's total energy use for material production.

Thormark [65] presents how material choice may affect both embodied energy and recycling potential in one of the most energy efficient apartment-type housing projects in Sweden (calculated energy for operation is 45 kWh/m^2 floor area per year). Initially, the embodied energy was 40% of total energy needed for a lifetime expectancy of 50 years. Through material substitution, the embodied energy can be decreased by approximately 17% or increased by about 6%.

Reddy [32] showed that in load-bearing masonry buildings, the total embodied energy of a conventional buildings (built with load-bearing brick-work, reinforced concrete solid slab floor and roof and concrete tile flooring) is 2.95 GJ/m^2, while in a building with alternative technologies (stabilized mud block masonry, SMB filler slab floor and roof, and terracotta tile flooring) is 1.53 GJ/m^2.

4. Embodied energy in building systems

Reddy [32] showed that the use of alternative low-energy building technologies results in about 50% reduction of the embodied energy of a building system. This statement is based on the embodied energy of walls, floor and roofing systems shown in Table 1.

5. Conclusions

While methodological studies talk about low energy materials, concrete studies on building materials always refer to embodied CO_2 or CO_2 footprint. Embodied energy has been defined by several authors, but there is general agreement that embodied energy in building materials has increased its importance in the life cycle of a building compared to operating energy, due to the better energy performance of the buildings. There is also a general agreement that embodied energy is difficult to quantify and that since there is no generally accepted methodology for its measurement or calculation, today's data disagree between authors and studies. A first approach to standardization of the embodied energy accounting in materials is presented by Dixit et al. [24].

The materials generally studied are cement and concrete, wood, bricks, rammed earth and sandstone. Finally, some literature can be found on the effect of material substitution in the embodied energy of a building.

It is interesting to also highlight that while negative environmental impact of housing construction is reduced, factors such as performance and economic viability are no compromised. Hamilton-MacLaren et al. [66] highlighted and studied the potential impact on customer appeal, and hence the economic viability of the use of alternative construction materials. If individuals are reluctant to purchase a house constructed using a particular technique, then its deployment is not possible, since the construction industry may not adopt it due to the low potential for sales and high risk of financial loss. Identification of those construction techniques acceptable to purchasers is of high importance.

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